Magnitudes and source areas of large prehistoric northern Alpine earthquakes revealed by slope failures in lakes

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ABSTRACT

We identify evidence for three large paleo-earthquakes in central Switzerland with moment magnitudes (M > 6.5–7.0) significantly exceeding historically known values. These earthquakes occurred during the past 15 k.y. and were strong enough to simultaneously affect a large region that includes the present-day major cities of Lucerne and Zurich. We reconstruct the chronology, magnitudes, and epicenters of these prehistoric earthquakes using temporal and spatial correlation of multiple subaqueous landslide deposits in Lake Zurich and Lake Lucerne through high-resolution seismic surveys, radiocarbon-dated sediment cores, and spatial calculations using an empirical seismic attenuation model. Our data indicate ongoing Alpine deformation that generated and could potentially generate destructive events in heavily populated regions that have been unaccustomed to seismic activity during historic time.

Keywords: paleoseismology, lacustrine sedimentation, slumps, earthquake magnitude, seismotectonics.

INTRODUCTION

Long-term earthquake models and probabilistic seismic hazard assessments require knowledge of a well-dated and quantitative earthquake history. In intraplate continental regions with low crustal deformation rates, the recurrence interval of strong earthquakes often exceeds the time span covered by instrumental and historical records, making seismically active fault zones difficult to identify. Hence, knowledge about the temporal and spatial distribution of prehistoric seismic events with long recurrence intervals is essential for understanding regional seismicity and for assessing the earthquake hazard potential of such regions. During the past 30 yr, paleoseismology has provided a wealth of information about paleoseismicity in a variety of geologic settings (Michetti et al., 2005; Vittori et al., 1991). This information usually relates to identification of specific events on recognized active faults (Sieh, 1978) or to more general descriptions of secondary effects (i.e., soil liquefaction, elevation changes, landslides) suggesting the occurrence of a prehistoric event (Keefer, 2002; Sims, 1975). However, earthquake parameter determination from only secondary effects still poses a challenge in paleoseismic research (Michetti et al., 2005). Here we determine the chronology, magnitudes, and epicenters for the intraplate area of central Switzerland by correlating in time and space sedimentary deposits of seismically triggered subaquatic lacustrine landslides, and by spatial macroseismic reconstructions using a grid-search approach with a calibrated intensity attenuation model.

Large earthquakes often spur mass movements, such as subaqueous landslides, that are recorded in sedimentary archives (Hampton et al., 1996). On 18 September 1601, the greater Lucerne area in central Switzerland was hit by one of the largest known earthquakes in central Europe (moment magnitude M = 6.2) that damaged parts of the city of Lucerne and its surroundings (Schwarz-Zanetti et al., 2003). The villages along the shoreline of Lake Lucerne experienced waves as high as 4 m and a subsequent seiche that lasted several hours. These effects were produced by 13 synchronous earthquake-triggered subaquatic landslides in Lake Lucerne (Schnellmann et al., 2002). In the temporally and spatially continuous sediments of peri-alpine lakes in central Switzerland, coeval mass-movement deposits can thus be tracked throughout the entire basin as the ''fingerprint'' of prehistoric seismic events. We studied the basins of Lake Zurich and Lake Lucerne (Fig. 1), wherein paleoseismic shaking can be singled out as the trigger mechanism; these basins lack major stream deltas and lake-level fluctuations are minor, so that additional potential trigger mechanisms for

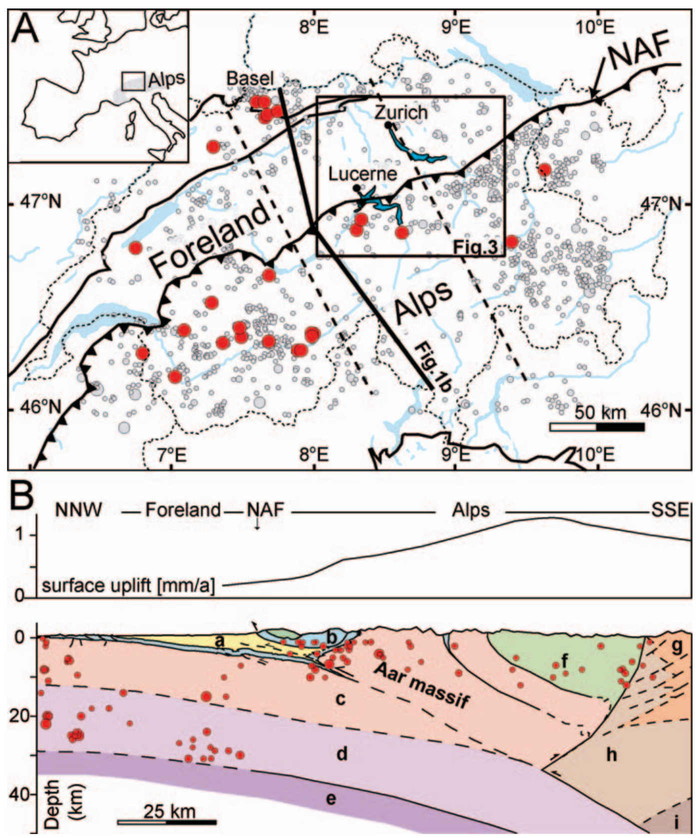

Figure 1. A: Location map showing tectonic units and epicenters of instrumentally (gray dots) and historically (M ≥ 5.5, red dots) recorded earthquakes (Fäh et al., 2003). Box in center locates study area with Lake Zurich and Lake Lucerne. Profile line and swath (dashed lines) indicate Alpine profile and maximum earthquake-projection distance in B. NAF is North Alpine nappe front. B: Present-day uplift rates (after Schlatter and Marti, 2002) along Alpine tectonic profile (after Pfiffner and Heitzmann, 1997; Pfiffner and Kühni, 2001) with depth distribution of known earthquake (M > 2) hypocenters since 1975 (Deichmann et al., 2000). a—Molasse basin, b—European margin (EM) Mesozoic cover, c—EM upper crustal basement, d—EM lower crust, e—EM mantle, f—Penninic upper crustal basement and cover, g—Apulian plate (AP) upper crust and cover, h—AP lower crust, i—AP mantle.

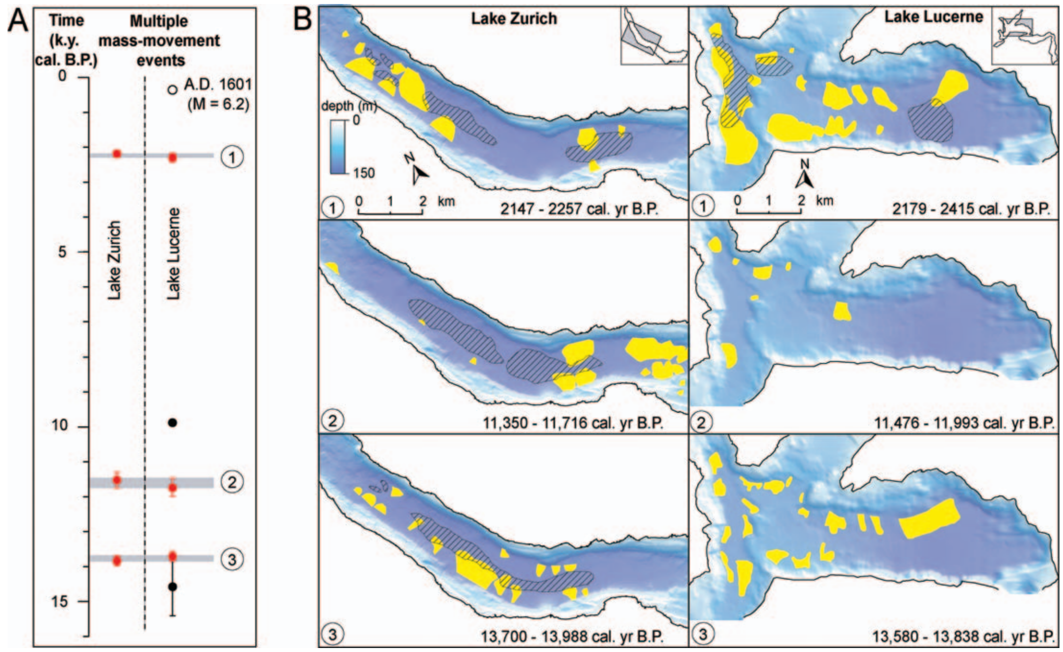

Figure 2. A: Correlation between dated (calibrated yr B.P.) multiple mass-movement events assigned to paleo-earthquakes in Lakes Zurich (this study) and Lucerne (Schnellmann et al., 2006). Black open circle indicates historic A.D. 1601 (moment magnitude M = 6.2) earthquake; black dots correspond to prehistoric regional events similar to A.D. 1601 event that are not recorded in Lake Zurich; and red dots correspond to three large prehistoric earthquakes recorded in both lakes (numbered 1–3). Gray bars indicate age-range overlap of two dated layers in both lakes. B: Maps showing simultaneous multiple mass-movement deposits (yellow areas) in both lakes for three large paleo-earthquakes. Hachured areas mark extent of turbidite deposits associated with landslides.

multiple slope failures can be excluded (Hampton et al., 1996). Furthermore, lacustrine landslide deposits in such settings record this intensity threshold of seismic shaking independent of the earthquake focal mechanism as revealed by calibration of multiple landslide deposits associated with historic earthquakes in central Switzerland. This demonstrates that sublacustrine slope failures occurred only within areas that underwent shaking of macroseismic intensities (EMS98) VII or more (Monecke et al., 2004). These sedimentary archives are thus critical components for quantitatively assessing the seismic hazard potential in a region that includes the major urban centers of Zurich and Lucerne, which have high population densities and key communications nodes.

SEISMOTECTONIC SETTING

Lucerne and Zurich are situated in the North Alpine foreland basin, 7 and 40 km north of the North Alpine nappe front, respectively (Fig. 1). This frontal thrust strikes WSW-ENE and marks the northern topographic boundary of the Alpine nappes formed during the Tertiary collision between Europe and Africa. In the foreland, earthquakes generally occur throughout the crust to Moho level (~30 km), nucleating in crystalline basement with predominantly strike-slip focal mechanisms and minor normal faulting components. Upper-crust shallow thrust and strike-slip faulting dominate the external Alpine nappes (Kastrup et al., 2004). The observed change in earthquake depth distribution and style of faulting between the foreland and the inner alpine zones reflects the superposition of the regional compressional stress, induced by large-scale continental convergence, the uniaxial tensional stress being related to lateral spreading within the Alpine orogenic belt (Kastrup et al., 2004). This is in agreement with the overall central alpine geodynamic situation characterized by the indentation of the Adriatic block into the European plate (Fig. 1) and isostatic plate forces acting on the steeply SSW-dipping lithosperic slab (Kissling, 2004). It further suggests that the Aar massif basement uplift (Fig. 1) is still growing in response to ongoing Alpine collision (Persaud and Pfiffner, 2004).

In the foreland, the largest known historic earthquake (M = 5.4) occurred in A.D. 1674 near Thalwil, ~20 km southeast of Zurich (Fäh et al., 2003); the inner alpine central Switzerland region south of Lucerne was seismically more active throughout history. Three events with M ≥ 5.7 were chronicled during the past 1 k.y., including the A.D. 1601 M = 6.2 event that may be associated with an ~20-km-long, left-lateral strike-slip fault system (Sarnen fault system) (Gisler et al., 2004). However, the historical record of seismicity in central Switzerland spans only ~1 k.y., and certainly does not reflect the overall seismic potential. Previous paleoseismological studies in Lake Lucerne calibrated the effect of seismic shaking in lake basins using the A.D. 1601 earthquake and identified 5 additional paleoseismic events (with effects similar to those produced by the A.D. 1601 event) that occurred in the past 15 k.y. (Schnellmann et al., 2006). Due to the limited geographical distribution of the investigated archives, however, estimations of epicenters and magnitudes remained dubious.

PALEOSEISMOLOGIC OBSERVATION IN LAKE ZURICH

To identify the occurrence of strong prehistoric seismic shaking in the foreland area of Zurich, we examined sediments in Lake Zurich for characteristic multiple landslide patterns by surveying a dense grid of high-resolution seismic profiles (3.5 kHz pinger source). We identified numerous landslide deposits in the seismic data based on chaotic to transparent seismic facies that contrast with continuous reflections produced by regular undisturbed sediments (Data Repository Fig. DR1[1]). We then connected the top of each mass-movement deposit at its pinch-out point with a distinct seismic-stratigraphic horizon. Such horizons represent isochrons that can be traced throughout the lake basin, allowing recognition of synchronous landslide events. We identified three event horizons, each comprising at least 10 individual mass-movement deposits across the entire lake basin. In the deepest part of the lake, these event horizons are associated with multiple stacked turbidite deposits lacking intercalated background sediment (Fig. DR2; see footnote 1), confirming the simultaneity of individual sublacustrine landslides derived from source areas of varying distance. In analogy to observations in Lake Lucerne, we interpret these three event horizons as subsurface ''fingerprints'' of three prehistoric earthquakes.

To date these earthquakes we retrieved six piston cores, as long as 11 m, from key locations identified in the seismic data. Each of the three seismic-stratigraphic multiple landslide horizons were dated in-

[1]GSA Data Repository item 2006221, grid search approach explanatory notes, seismic data (Figure DR1), core data (Figure DR2), and ^{14}C date data (Tables DR1 and DR2), is available online at www.geosociety.org/pubs/ft2006.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

dependently three to five times by combining accelerator mass spectrometry ^{14}C analysis of terrestrial organic matter, tephrachronology, sedimentation rate, and seismic data–core correlations (Tables DR1 and DR2). The resulting ages of the three events are 2200 ± 55, 11,530 ± 185, and 13,840 ± 145 calibrated yr B.P.

These results indicate that every few thousand years, the foreland region of Zurich experienced seismic events strong enough to trigger basin-wide slope instabilities. The ages of these three events match the ages of three of five reconstructed prehistoric earthquakes recorded in Lake Lucerne (Schnellmann et al., 2006) (Fig. 2). This correlation indicates that three very large earthquakes shook central Switzerland in the past 15 k.y. and were strong enough to trigger multiple mass movements in these two lakes located ~40 km apart. Using the overlap of event-age ranges in both lakes, we date these events as 2220 ± 40, 11,600 ± 120, and 13,770 ± 70 cal. yr B.P. (Fig. 2).

SOURCE PARAMETER DETERMINATION

To estimate minimum magnitudes at epicentral locations required to produce mass movements in both lakes, we first assigned EMS98 intensities VII to the sites of lacustrine landslides in Lakes Zurich and Lucerne. This value is the accepted threshold intensity for basinwide landsliding that was calibrated with historic earthquakes in central Switzerland (Monecke et al., 2004). We then calculated magnitudes over a grid of trial source locations (Bakun and Wentworth, 1997) using an empirical intensity attenuation relation (Fäh et al., 2003), a function of epicentral distance and hypocentral depth (Data Repository; see footnote 1). Based on geologic, structural, and seismotectonic information (Fig. 1) (Kastrup et al., 2004), we selected a deeper average depth for events in the foreland, and a shallower depth for potential Alpine thrust fault scenarios south of the North Alpine nappe front. The result of this grid-search approach indicates a minimum required magnitude of M = 6.5 if all three events were centrally located between the two lakes, whereas values approaching and exceeding M = 7 are required if the events were located farther away (Fig. 3).

To further define the potential epicentral area, we considered other well-established lacustrine paleoseismic archives within a radius of 60 km from the study area (Monecke et al., 2006) (Fig. 3). Lake Baldegger, west of the study area, has no earthquake-generated deposits identified in the critical periods for all three events; therefore, in the grid-search calculations that included the negative evidence, we assigned EMS98 intensities <VII to the Lake Baldegger site. Results reveal only valid solutions for a confined sector, suggesting that epicentral areas for all three seismic events were located to the east of Lake Lucerne and southeast of Lake Zurich (Fig. 3). Lake Seelisberg, a small mountain lake south of Lake Lucerne with specific characteristics not comparable to the other lakes and therefore not considered for grid-search calculations, shows positive evidence for seismically induced deformations dated to 11,660 ± 590 cal. yr B.P. (Monecke et al., 2006) This further confirms the occurrence of a large paleo-earthquake ca. 11,600 cal. yr B.P.

DISCUSSION

Due to the absence of known seismogenic faults with surface ruptures and the lack of direct observations in the instrumental and historical catalogue, the location and geometry of faults capable of producing the three large prehistoric earthquakes cannot be identified directly. Nevertheless, plausible earthquake scenarios may be formulated using geologic, structural, and seismotectonic information (Fig. 1), including the general stress regime for the areas northwest and southeast of the North Alpine nappe front (Kastrup et al., 2004) and generally accepted relationships between magnitudes and rupture area (Wells and Coppersmith, 1994) (Fig. 3). The spatial reconstruction suggests that large prehistoric earthquakes were probably not related to the historically active Sarnen strike-slip fault system south of Lake

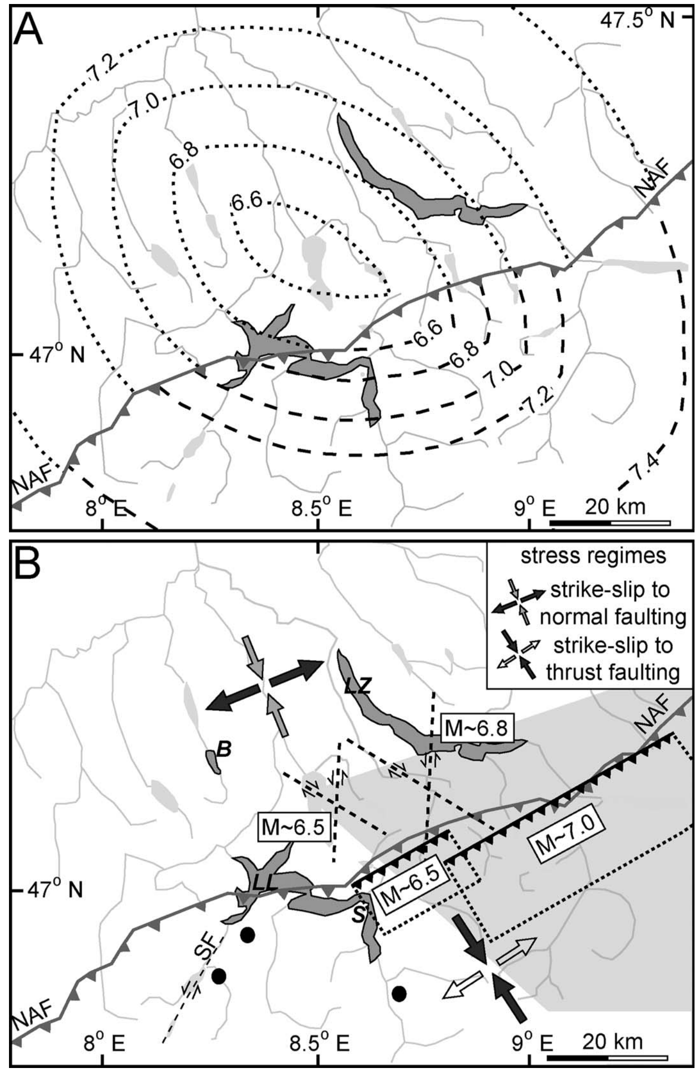

Figure 3. A: Zones of earthquake epicenters (dotted and dashed lines for deep foreland and shallow northern Alpine source, respectively) of minimum given magnitude sufficient to produce observed landslides in Lake Zurich and Lake Lucerne, identified by grid-search approach (Bakun and Wentworth, 1997). NAF is North Alpine nappe front. B: Map showing possible epicentral locations (shaded area) satisfying positive and negative paleoseismologic evidences in different lake archives (LZ—Lake Zurich, LL—Lake Lucerne, B—Lake Baldegger, S—Lake Seelisberg). Arrows indicate two different stress regimes in foreland and Alpine setting (Kastrup et al., 2004). Superimposed black dashed lines and rectangles conceptually indicate potential Alpine foreland strike-slip fault orientations and projected rupture areas of thrust-type earthquakes, respectively (Wells and Coppersmith, 1994), as expected in present stress field. Note that exact locations of faults are speculative; to date, no seismogenic faults are known in area. Black dots south of Lake Lucerne indicate epicenters of three historical earthquakes (M ≥ 5.7) and black dashed line southwest of Lake Lucerne indicates known ~20-km-long seismically active Sarnen strike-slip fault system (SF) (Gisler et al., 2004).

Lucerne. Furthermore, the calculated magnitude of an event located south of Lake Lucerne would be M ≥ 7.2 and rupture length would be ≥60 km (Wells and Coppersmith, 1994), whereas the observed length of the Sarnen fault system is only ~20 km.

A possible scenario involves a deep-seated strike-slip fault below the foreland basin, capable of producing M ≥ 6.5 events. With the present regional stress regime in the northern Alpine foreland (Kastrup et al., 2004), such a seismogenic fault would strike NW-SE (dextral) or N-S (sinistral), which is in agreement with a recently identified, seismically active N-S-trending sinistral strike-slip fault in the crystalline basement below the western Swiss molasse basin (Kastrup, 2002).

An Alpine thrust fault system that strikes parallel to the front of the Alpine nappes is a second and geologically more plausible scenario that could produce the required M 6.5–7.0 event. In the east of the study area, where instrumental earthquake data indicate thrust fault focal mechanisms close to the North Alpine nappe front (2 April 1989 in Weesen, M = 3; Fäh et al., 2003), the calculated minimal magnitude would amount to M ~ 7. Such earthquakes could be produced by release of accumulated NW-SE compressional stress related to an active basal thrust beneath the Aar massif, along which the central Aar massif is overthrusted onto the autochthonous foreland cover and forms a growing fault-propagation fold (Fig. 1). Driving forces for such a major thrust fault might be ongoing Alpine collision (Persaud and Pfiffner, 2004) and/or isostatic plate forces acting on the northwestward-retreating European lithospheric slab (Kissling, 2004). Postglacial faults in the eastern Swiss Alps (Persaud and Pfiffner, 2004) and strong NW-SE gradients in surface-uplift rates across the northern front of the Aar massif (Schlatter and Marti, 2002) (Fig. 1) provide further support for an active basal thust beneath the Aare massif.

CONCLUSION

We identify three prehistoric earthquakes more intense than any historically known earthquake in the Alpine area (A.D. 1601, M = 6.2) and much more intense than those recorded in the foreland (A.D. 1674, M = 5.4). These prehistoric events are comparable to the largest historically documented earthquake in central Europe (Basel, A.D. 1356, M = 6.9; Meghraoui et al., 2001). They also affected the location of present-day Zurich, a densely populated region that was previously believed to be free of major seismic hazards. Furthermore, the occurrence of three strong events along the northern Alpine topographic front within the past 15 k.y. indicates active Alpine deformation that could generate rare but destructive events in the future.

We conclude that temporal and spatial correlation of precisely dated paleoseismologic archives, such as the record of sublacustrine landslide deposits, is a valuable tool to constrain chronology, magnitudes, and epicenters of prehistoric seismicity. This approach is especially critical in intraplate settings, often characterized by faults that lack surface expression and produce events on time scales much longer than recorded human history.

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REFERENCES CITED

Bakun, W.H., and Wentworth, C.M., 1997, Estimating earthquake location and magnitude from seismic intensity data: Seismological Society of America Bulletin, v. 87, p. 1502–1521.

Deichmann, N., Baer, M., Braunmiller, J., Dolfin, D.B., Bay, F., Delouis, B., Fäh, D., Giardini, D., Kastrup, U., Kind, F., Kradolfer, U., Kunzle, W., Rothlisberger, S., Schler, T., Salichon, J., Sellami, S., Spuhler, E., and Wiemer, S., 2000, Earthquakes in Switzerland and surrounding regions during 1999: Eclogae Geologicae Helvetiae, v. 93, p. 395–406.

Fäh, D., and 22 others, 2003, Earthquake catalogue of Switzerland (ECOS) and the related macroseismic database: Eclogae Geologicae Helvetiae, v. 96, p. 219–236.

Gisler, M., Fäh, D., and Kästli, P., 2004, Historical seismicity in central Switzerland: Eclogae Geologicae Helvetiae, v. 97, p. 221–236, doi: 10.1007/s00015-004-1128-3.

Hampton, M.A., Lee, H.J., and Locat, J., 1996, Submarine landslides: Reviews of Geophysics, v. 34, p. 33–59, doi: 10.1029/95RG03287.

Kastrup, U., 2002, Seismotectonics and stress field variations in Switzerland [Ph.D. thesis]: Geological Institute, ETH Zurich, Switzerland, 153 p.

Kastrup, U., Zoback, M.L., Deichmann, N., Evans, K.F., Giardini, D., and Michael, A.J., 2004, Stress field variations in the Swiss Alps and the northern Alpine foreland derived from inversion of fault plane solutions: Journal of Geophysical Research-Solid Earth, v. 109, p. B01402, doi: 10.1029/2003JB002550.

Keefer, D.K., 2002, Investigating landslides caused by earthquakes—A historical review: Surveys in Geophysics, v. 23, p. 473–510, doi: 10.1023/A:1021274710840.

Kissling, E., 2004, Alpine orogeny and seismicity in Switzerland: 2nd Swiss Geoscience Meeting, Lausanne, Abstracts: Lausanne, Switzerland, Faculté des Géosciences et de l'Environnement, Université de Lausanne, p. 210.

Meghraoui, M., Delouis, B., Ferry, M., Giardini, D., Huggenberger, P., Spottke, I., and Granet, M., 2001, Active normal faulting in the upper Rhine graben and paleoseismic identification of the 1356 Basel earthquake: Science, v. 293, p. 2070–2073, doi: 10.1126/science.1010618.

Michetti, A.M., Audemard, F.A., and Marco, S., 2005, Future trends in paleoseismology: Integrated study of the seismic landscape as a vital tool in seismic hazard analyses: Tectonophysics, v. 408, p. 3–21, doi: 10.1016/j.tecto.2005.05.035.

Monecke, K., Anselmetti, F.S., Becker, A., Sturm, M., and Giardini, D., 2004, The record of historic earthquakes in lake sediments of central Switzerland: Tectonophysics, v. 394, p. 21–40, doi: 10.1016/j.tecto.2004.07.053.

Monecke, K., Anselmetti, F.S., Becker, A., Schnellmannn, M., Sturm, M., and Giardini, D., 2006, Earthquake-induced deformations structures in modern lake deposits—The paleoseismic record of central Switzerland: Eclogae Geologicae Helvetiae (in press).

Persaud, M., and Pfiffner, O.A., 2004, Active deformation in the eastern Swiss Alps: Post-glacial faults, seismicity and surface uplift: Tectonophysics, v. 385, p. 59–84, doi: 10.1016/j.tecto.2004.04.020.

Pfiffner, O.A., and Heitzmann, P., 1997, Titel, *in* Pfiffner, O.A., et al., eds., NRP 20—Deep structure of the Swiss Alps: Basel, Birkhäuser, p. 115–122.

Pfiffner, O.A., and Kühni, A., 2001, Geological and hydrological profiles, Part 1: Geology, *in* Spreafico, M., ed., Hydrological atlas of Switzerland: Bern, Switzerland, Swiss Federal Office of Water and Geology.

Schlatter, A., and Marti, U., 2002, Neues Landeshöhennetz der Schweiz LHN95: Vermessung, Photogrammetrie, Kulturtechnik, v. 1, p. 13–17.

Schnellmann, M., Anselmetti Flavio, S., Giardini, D., McKenzie, J.A., and Ward, S.N., 2002, Prehistoric earthquake history revealed by lacustrine slump deposits: Geology, v. 30, p. 1131–1134, doi: 10.1130/0091-7613(2002)030<1131:PEHRBL>2.0.CO;2.

Schnellmann, M., Anselmetti, F.S., Giardini, D., and McKenzie, J.A., 2006, 15,000 years of mass-movement history in Lake Lucerne: Implications for seismic and tsunami hazard: Eclogae Geologicae Helvetiae (in press).

Schwarz-Zanetti, G., Deichmann, N., Fäh, D., Giardini, D., Jimenez, M.J., Masciadri, V., Schibler, R., and Schnellman, M., 2003, The earthquake in Unterwalden on September 18, 1601: A historico-critical macroseismic evaluation: Eclogae Geologicae Helvetiae, v. 96, p. 441–450.

Sieh, K.E., 1978, Prehistoric large earthquakes produced by slip on San Andreas fault at Pallett Creek, California: Journal of Geophysical Research, v. 83, p. 3907–3939.

Sims, J.D., 1975, Determining earthquake recurrence intervals from deformational structures in young lacustrine sediments: Tectonophysics, v. 29, p. 141–152, doi: 10.1016/0040-1951(75)90139-0.

Vittori, E., Labini, S.S., and Serva, L., 1991, Palaeoseismology—Review of the state-of-the-art: Tectonophysics, v. 193, p. 9–32, doi: 10.1016/0040-1951(91)90185-U.

Wells, D.L., and Coppersmith, K.J., 1994, New empirical relationships among magnitude, rupture length, rupture width, rupture area, and surface displacement: Seismological Society of America Bulletin, v. 84, p. 974–1002.

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